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SHOCK WAVES FROM EXPLODING WIRES AT

LOW AMBIENT DENSITIES

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BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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F. D. Bennett/D.D. Shear/lc
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ABSTRACT

Shock waves from exploding wires at subatmospheric density ρ_o show considerable deviations from the $\rho_o^{-1/4}$ dependence of shock radius expected on the basis of blast wave theory. The shock trajectory data are consistent with the assumption of time dependent energy addition and this fact suggests complexity in the mechanism of shock production. The recently discovered technique of streak interferometry has been applied to study 4 mil Cu wires exploded into argon at reduced pressures. Typical interferograms at 1/16 atm show an intensely luminous, peripheral arc formed in an annulus several millimeters from the wire. When filters are used to diminish the diffuse light from the glow, clear fringes can be reduced in the entire glowing region. Near the tip, measured fringe-shifts are negative indicating the presence of electrons. No shock wave is seen. During an interval of about 1 μsec fringe-shifts near the periphery of the expanding glow change to positive values and a compressional shock wave can be seen to separate and propagate ahead. Estimates obtained from approximate interferogram reductions indicate electron densities as high as 10^{18}/cc in the annular region of the arc. A sequence of interferograms at pressures 1/16 to 1 atm is presented and implications for the mechanism of shock production are discussed.

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1. INTRODUCTION

In a paper given at the first Conference on Exploding Wires [1] data were presented showing large deviations from the $\rho_o^{-1/4}$ dependence of shock radius on ambient density predicted by blast wave theory. We reconsider this problem here in the light of new data obtained by the method of streak interferometry. The main result which will be obtained is that shock production by exploding wires does not proceed from the unconfined expansion of the heated metal vapor alone, but depends on a two stage process in which the early expansion of a plasma created by the peripheral arc plays an important part, especially at the lower pressures.

The present study is introductory in the sense that new and complex phenomena are revealed, but full quantitative descriptions cannot yet be given.

2. EXPERIMENTAL

2.1 Modifications in Technique

Streak interferometry at atmospheric pressure has already been described in detail[2]. Equipment changes necessary to adapt the technique to other than atmospheric pressures are shown in Figs. 1-4. These include 1) a tank fitted with high quality optical glass windows, seen in Fig. 1, and capable of withstanding pressures from 0 to 10 atm, 2) a bakelite mounting, (Fig. 2), to support the wire in the interferometer beam, and 3) suitable coaxial leads to conduct the current from the externally located condensers and triggering spark to the exploding wire, Fig. 3. The circuit is similar to those used previously and contains approximately 0.3 μf at 20 kv. Ringing frequency is 0.4 mc. Stored energy per cm of wire is 29 joules .

2.2 Interferograms

Fig. 5 (a) shows a streak interferogram taken at 1/16 atm in argon with monochromatic backlighting and no attempt made to filter the direct glow. The result is not an interferogram which can be reduced; but nevertheless one in which some interesting and important features can be observed. The outline of the wire can be seen as it expands inside the peripheral arc which starts several millimeters from the wire. The arc propagates very rapidly both in toward the wire and outward in the radial direction thus forming the toroidal annulus which characterizes the foremost luminosity. Some of the factors governing the peripheral arc have been discussed previously[3], but the basis for understanding how the shape and size of the arc depend on pressure has not yet been explicitly stated. We postpone consideration of this interesting problem to a later paper. Actually the luminous intensity of the arc is very much greater than Fig. 5(a) suggests; for in order to bring out details, the luminosity has been partially suppressed in the reproduction.

The main features important to this study are 1) the tendency of fringes entering the glow to shift upwards, and 2) the lines of downward

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fringe shift seen slightly outside the glowing region on both upper and lower sides of the interferogram, and beginning about 1.6 μsec after the arc. We interpret these lines of discontinuity as the traces of the compressive shock produced by the arc and wire. On this assumption we see that fringe-shift for a compression of the gas, which necessarily entails increased density and increased index of refraction, is in the downward direction. The first upward fringe shift must then represent a relative decrease in the index of the refractive medium. There are only two reasonable possibilities to explain this decrease. Either the ex-istence of a sudden expansion of the gas or the presence of light, negative charges would be sufficient to cause the inferred decrease in index of refraction.

We rule out the first possibility on the grounds that sharply defined expansion fronts not preceded by shock waves would violate the principle of increase of entropy, and in fact, are never encountered in shock tubes or supersonic flows. However, negative fringe-shifts caused by electron concentrations are observed in strong, ionizing shock waves[4]. We are thus led to the conclusion that the negative fringe-shifts must be associated with the presence of free electrons, a conclusion which is compatible both with the high electrical conductivity and with the intense radiation of the peripheral arc.

To remove the objectionable direct glow which obscures part of the fringe field, two further modifications in the experimental technique are employed. The monochromator is removed entirely from the optical train and an interference filter centered on the green mercury line at 5460 A, with a pass band of about 100 A, placed in the exit interferometer beam. This is followed by a "minus blue" filter which cuts out wave lengths less than 5000 A, put between the camera lens and the rotating mirror. Finally, the film used, viz. Royal-ortho, tends to eliminate wave lengths above 5700 A. With these changes good interferograms have been obtained at 1/16, 1/8, and 1/4 atm, see Figs. 5 - 6. Significant but nonreducible interferograms have been obtained at 1/2 and 1 atm and are shown in Fig. 6.

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2.3 Interferogram Reduction

The problem of reduction of an axisymmetric interferogram, where fringe-shifts are caused by varying concentrations of atoms, ions, and electrons, can be solved by combining and elaborating reduction schemes already worked out.[4, 5, 6] Simultaneous interferograms at two different wave lengths are necessary in order to separate, at every point in the field of observation, electron effects from those of polarizable atoms and ions. While the computational program of a two interferogram reduction can readily be prescribed for electronic machines such as ORDVAC, the experimental technique for producing the simultaneous interferograms has not yet been fully developed. For this reason we are unable to analyze the whole fringe field in detail, but must limit ourselves to an approximate reduction scheme applicable only to the initial regions of the single interferograms already available.

We assume the following: 1) the disturbance is axially symmetrical, 2) argon ions and neutrals have equal polarizabilities and 3) initially, atoms and ions remain at room temperature.

These assumptions require some comment. Measurement of the interferograms shows departures from symmetry about the central line, probably associated with asymmetries of the magnetic field produced by the entire circuit. Upper and lower halves can be reduced separately under the assumption that each is individually axially symmetric. Disagreement between values obtained at corresponding points in the upper and lower halves runs as high as $\pm$ 20% and is probably indicative of the maximum error introduced by departures from cylindrical symmetry.

Regarding the second assumption, Alpher and White[4] estimate the specific refractivity of the argon ion to be about 0.7 that of the atom. If density changes can be ignored, as assumption 3) implies, then the production of ions affects the total refractivity in the same sense as the concomitantly appearing electrons; but the electron refractivity is nearly twenty times as large and therefore dominates. It is easily shown that lumping ions together with the atoms increases the calculated electron concentrations only by about 3%.

Finally, assumption 3) assures that refractive effects of ions and atoms in the disturbed beam exactly cancel those of the atoms in the undisturbed beam. The resulting fringe shift is then interpretable as being due to electrons alone. Even where this assumption is only approximately fulfilled, electron effects will dominate if ionization is greater than 10% because of the much larger refractivity of the electrons. The third assumption is strictly true only in a small region near the beginning of the glow where the negative fringe-shift is largest in magnitude. Just before the compression shock wave appears, one easily finds a region of considerable size where fringes are practically undeviated and fringe-shift is zero (see Figs. 5-6). Clearly, here the negative shift caused by electrons is balanced by the positive shift caused by compression of ions and atoms and assumption 3) must fail. Therefore our reduction is limited to the area occurring to the left of the zero fringe-shift regions and the assumption is increasingly well fulfilled toward the tip of the disturbance.

Two further questions remain to be discussed: first, is birefringence of the electron cloud in the magnetic field about the wire a complicating factor; and second, can the classical dispersion relation for an electron gas be employed?

Following the treatments of electron double-refraction given by Stratton[7] and Spitzer[8], we see that the ratio of electron cyclotron frequency ω_{ce} to frequency of light ω, must be small if ordinary and extraordinary rays are to have the same velocity and remain indistinguishable. Fields up to 10^6 gauss can occur near the surface of the wire, but even for this maximum field the inequality $\omega_{ce}/\omega < .01$ is satisfied. Double refraction can be ruled out.

In order to use the classical electron dispersion relation it is necessary that the plasma frequency ω_p and the electron collision frequency ω_{coll} both be small compared with the frequency of light. Using the conventional definitions and Spitzer's treatment of the collision time, (ref. 8, p. 77), specialized to electrons moving through nearly stationary, heavy ions we find that at the highest pressure used in this study, viz.,

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1 atm, neither of the rations ω_p/ω, ω_{coll}/ω exceeds 0.06; thus the error incurred by dropping terms higher than the squares is no larger than about 0.4 percent.

Making use of the simplifying assumptions discussed above, we can write the expression for electron concentration N_e, in particles per cm^3, as

$$N_e(u_i,t) = 2.60 \ 10^{17} \int_{u_i}^{u_n} (d\delta/du) \ d\sqrt{u-u_i} \qquad (1)$$

where $u = r^2$, r is radial distance in cm, δ is fringe-shift and u_i, u_n designate the inner selected point and outer boundary respectively, of the disturbance on a vertical trace constructed at time t on the horizontal axis. The wave length of light is taken as 5460 A.

The technique of reduction is to measure δ on several traces near the tip of the disturbance and for each to make a plot of δ vs. u. Each curve is then approximated by straight line segments. We find that, in the restricted region examined, four or fewer segments will suffice. The integral (1) can then be expressed as a sum of not more than four terms, and computations of electron densities at selected points made immediately. This procedure has the disadvantage that the electron density curve will exhibit at each tie point of the linear segments, a parabolic rise with magnitude and sign depending on the size and direction of the slope change in going from one segment to the adjoining one through the tie point.[6] However, except for the outside boundary u_n, where the effect is real, a little judicious smoothing applied to the resulting N_e curve will mitigate parabolic rises which inspection shows to be inconsistent with the trend of the fringe-shift curve.

Curves of constant electron density for the 1/16, 1/8 and 1/4 atm cases are shown in Figs. 7-9. One sees that the contours follow with reasonable accuracy the general shape of the glow (cf. Fig. 5) and that higher electron concentrations occur closer to the axis where luminosity

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is also more intense. Maximum percentage ionizations encountered in the three cases are roughly 65, 50 and 35% and occur at small radii before very much expansion of the wire has occurred. The apparent tendency of N_e to decrease after 1 μsec has elapsed, is partially due to the compensating effect of compression of the gas which culminates in the appearance of the outward moving shock wave.

3.   DISCUSSION OF THE DATA.

3.1 Departure from Blast Wave Theory

As noted in our previous paper[1] a dependence on ambient density of the energy delivered to the exploding wire could account for the deviations from the $\rho_0^{-1/4}$ law reported there. Our subsequent study[3] demonstrates that such a dependence must exist, in showing that the peripheral arc through the surrounding medium appears during the critical interval of time when energy is being rapidly deposited in the expanding wire. Further, it is clear in the present cases that because of the reduction of ambient density, the voltage at which the peripheral arc occurs will necessarily be lowered. Inspection of the energy and voltage curves for the cases presented in reference 3 shows that, depending on the voltage level at which the arc forms, the energy deposited in the wire can vary between zero and the maximum indicated. The effect of the arc is to shunt the wire and rob it of the energy to be deposited by the shunted current.

Thus we see that the true situation radically violates the essential assumptions of blast wave theory, viz. that the energy be deposited instantaneously along a line. For the exploding wire at 1/16 atm a portion of the energy is deposited in the relatively small cross-section of the wire, while another, not necessarily smaller, amount is deposited in the much larger (by a factor of 10^3) annulus occupied by the peripheral arc.

Inspection of the sequence of interferograms from 1/16 to 1 atm, Figs. 6 - 10, shows that, with increasing pressure, the size of the arc, as measured by its diameter taken at the zeroth fringe-shift points, diminishes rapidly, but in a complicated way, as pressure increases. The rate of expansion of the wire at early times increases rapidly with increasing pressure, confirming the supposition that deposited energy is similarly increasing.

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At the higher ambient densities the compression shock merges increasingly well, tangentially to the curve defined by the luminosity bordering the expanding wire material. This is what one would expect if the shock were produced mainly by the sudden expansion of a cylindrical volume of hot metal vapor; for in such a case the shock, at an early time in its history, would appear to be in contact with the expanding vapor. Kerr cell photographs taken by Müller[9], for the case in which no peripheral arc appears, show quite well this stage in the development of a cylindrical shock wave.

In contrast with this model, at the lower pressures the compression shock is not continuous with the expanding wire material, but merges tangentially into the region occupied by the arc. The arc itself is initially a rapidly expanding region which we know to be highly ionized, and is now seen to be the probable origin of the outer compression shock wave. In the 1/16 atm case the fact that this wave is practically straight instead of decaying with time along a parabolic curve lends substance to the belief that energy carrying disturbances are reaching it along characteristic curves in the flow connecting its later stages with the earlier stages of the inner wire expansion. A single fringe interferogram of this case (not shown here) indicates also that a small shock disturbance, originating in the inward expansion of the arc annulus, reflects from the wire material near the tip and propagates outward to merge with the head shock wave at about $t = 3$ µsec. Thus energy is available to the head shock wave both from the arc and later from the wire expansion.

Finally, we observe that along the boundary of the more gradually expanding wire there are abrupt positive jumps in the fringes indicative of a density rise. It seems plausible to interpret this surface as the compression shock in argon caused by the wire expansion. On the other hand interpretation of a single fringe interferogram taken at 60µ pressure, where ambient gas can be completely neglected, suggests that it may represent a translucent cloud of metal particles at the outer edge of the expanding wire. Resolution of this question must wait until the effects of electrons can be separated from those of polarizable atoms and ions, through analysis of interferograms taken at different wave lengths.

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3.2 Mechanism of Shock Production

The mechanism of production of a shock wave by sudden expansion of a compressed gas can be analyzed with the help of modern computing machines. For cylindrical symmetry and specifically the case of exploding wires, Rouse[10] has made numerical calculations based on the conservation laws of fluid mechanics and appropriate assumed equations of state for air and for copper vapor. These theoretical results reproduce with reasonable fidelity the head shock wave and the interior, second shock wave for typical explosions of fine copper wires into air. On the basis of this work, we argue that at the higher ambient pressure, $p_o \gtrsim 1/2$ atm, the formation of shock waves by exploding wires can be successfully accounted for by the fluid mechanical theory. For the lower pressures, $p_o \lesssim 1/4$ atm, deviations from the blast wave theory, which forms a sort of zeroth order approximation to the full gasdynamical theory, are very marked and betoken the intervention of an hitherto unrecognized process of shock formation of negligible importance at the higher pressures.

The new process is, according to the discussion of § 3.1, intimately connected with the presence and development of the transient plasma caused by the peripheral arc. We accept tentatively the hypothesis that below $1/4$ atm ambient pressure, the head shock wave is caused principally by expansion of the arc plasma. To a lesser extent, expansion of the wire material may contribute energy to the shock, but the head shock wave is practically independent of the expansion of the wire at early times.

There seem to be two mechanisms by which an expanding plasma can initiate a shock wave. The first of these involves expansion of the plasma after heating to relatively high temperatures through collisions of electrons, rendered energetic by the longitudinal electric field, with ions and neutral atoms of the plasma. This is the analog in the gas, of the ohmic heating which ultimately expands the wire material.

The second mechanism discussed in two recent papers by R. G Fowler and co-workers [11], [12] involves expansion of the plasma because of Coulomb forces arising from charge separation, as the hot electron gas expands and draws the positive ions and neutrals with it, before temperature equilibrium can occur. Such a shock-producing mechanism regards the electron cloud as the principal driving mechanism and assigns negligible importance to collisional heating of the heavy particles by electrons.

Further analysis of these shock-producing mechanisms and their relevance to the present problem is beyond the scope of the present paper. Perhaps it is permissible to forecast that both must be present to some degree and it will be one of the tasks of future studies to determine the conditions under which each most prominently appears.

3.3 Summary

Streak interferograms have been obtained of 4 mil copper wires exploding in ambient atmospheres at pressures ranging from 1/16 to 1 atm. The conditions are examined under which these interferograms can be directly reduced to provide numerical values of electron concentrations. The assumptions underlying an approximate reduction scheme are discussed and it is shown that reasonably accurate values of electron concentration can be expected in a region near the tip of the explosion.

Analysis of the interferograms and comparison with other data shows that the wire explosion proceeds in two steps, viz. the first, in which a peripheral arc forms about the wire and effectively terminates the further deposit of electrical energy in the wire, followed continuously by the second, during which the wire expands inside the head shock wave and accompanying flow field created by the peripheral arc. Maximum electron concentrations occur at the lowest pressure studied, 1/16th atm, and indicate up to 65% ionization near the center of the arc plasma.

Analysis of the two stage mechanism by which the explosion takes place shows convincingly why, at the pressures, the head shock waves fail to follow the $\rho^{-1/4}$ law of blast wave theory. At the pressures $p < 1/4$ atm,

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the head shock is formed by expansion of the arc plasma which diverts energy from the exploding wire itself. Comparatively small amounts of energy are deposited in either the plasma expansion or in the following wire expansion, and the shock formed by the combination of these processes violates the blast wave assumptions of instantaneous energy release along a line. At higher pressures, $p \geqslant 1/4$ atm, the two steps are seen to merge and, with larger energy deposit in the wire material, the wire expansion dominates the process of shock formation.

Finally, a brief discussion is given of mechanisms by which the arc-plasma expansion can produce the head shock wave at the lower pressures. It is plausibly argued that both ohmic heating (collisional) and electron driving (Coulomb force) processes must be present.

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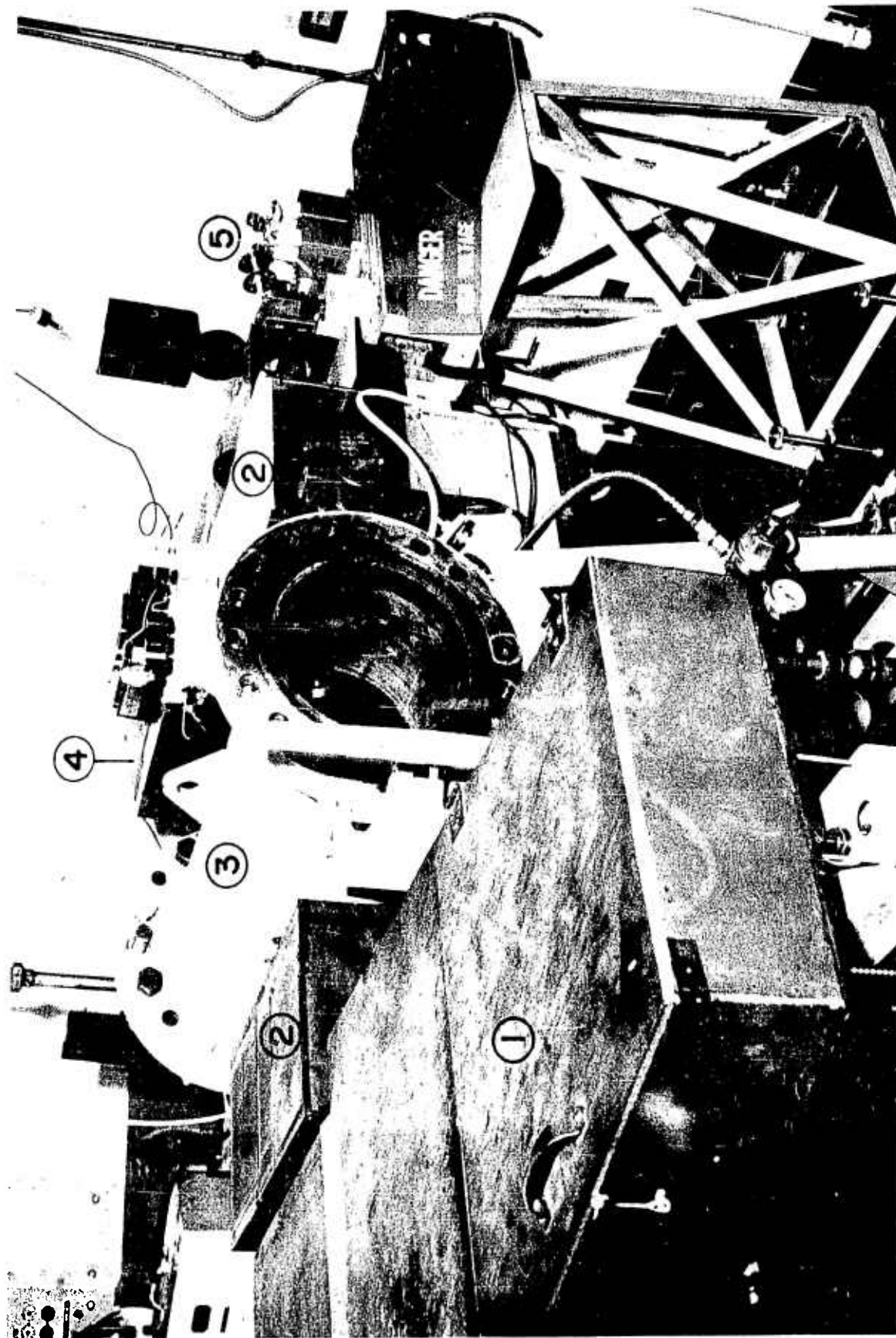
Fig. 1. View of Streak Interferometer - 1. camera, 2. Mach-Zehnder interferometer, 3. chamber, 4. monochromator, 5. auxiliary light source.

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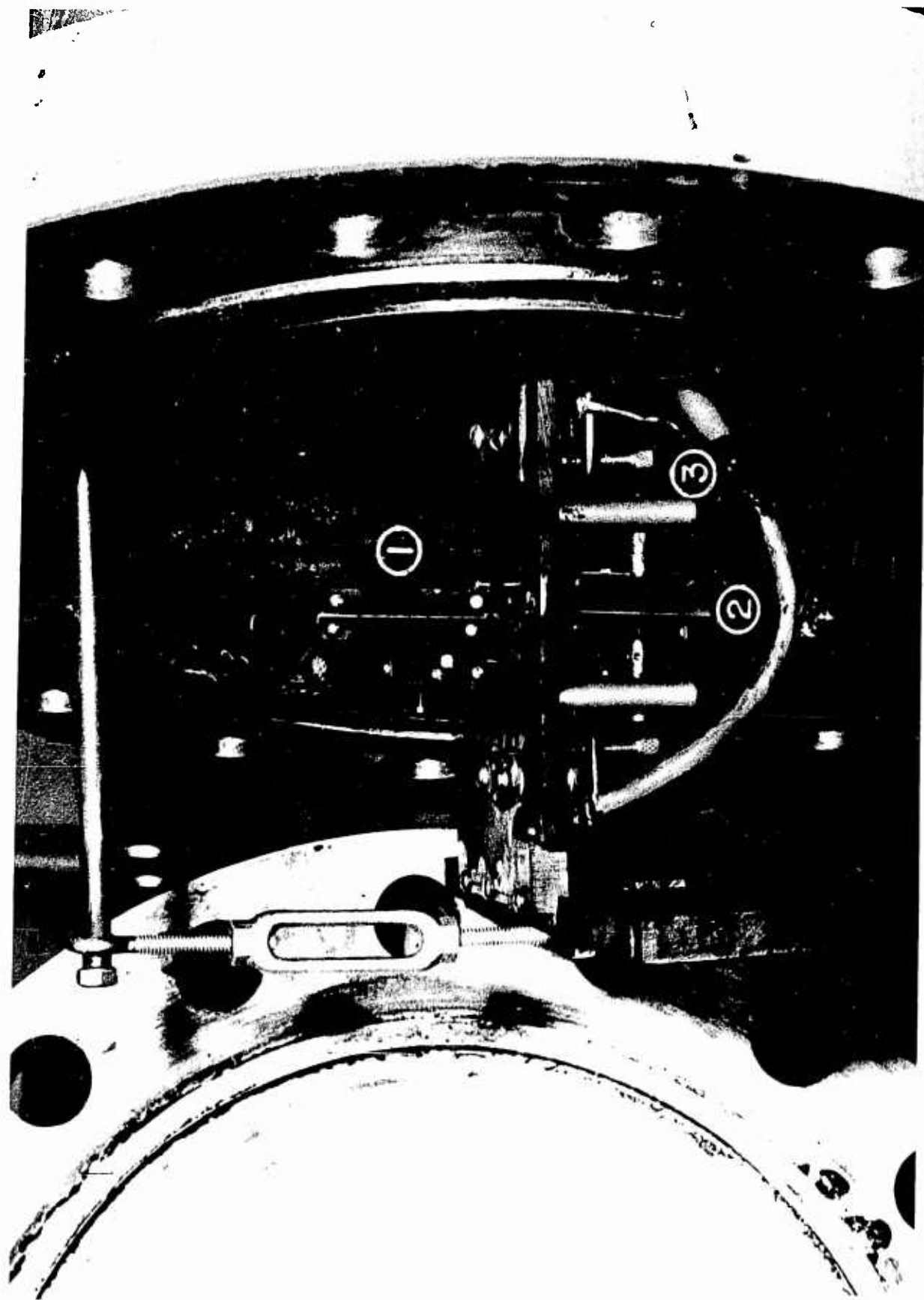
Fig. 2. Exploding Wire Mount - 1., 2. upper and lower slits, 3. wire holder.
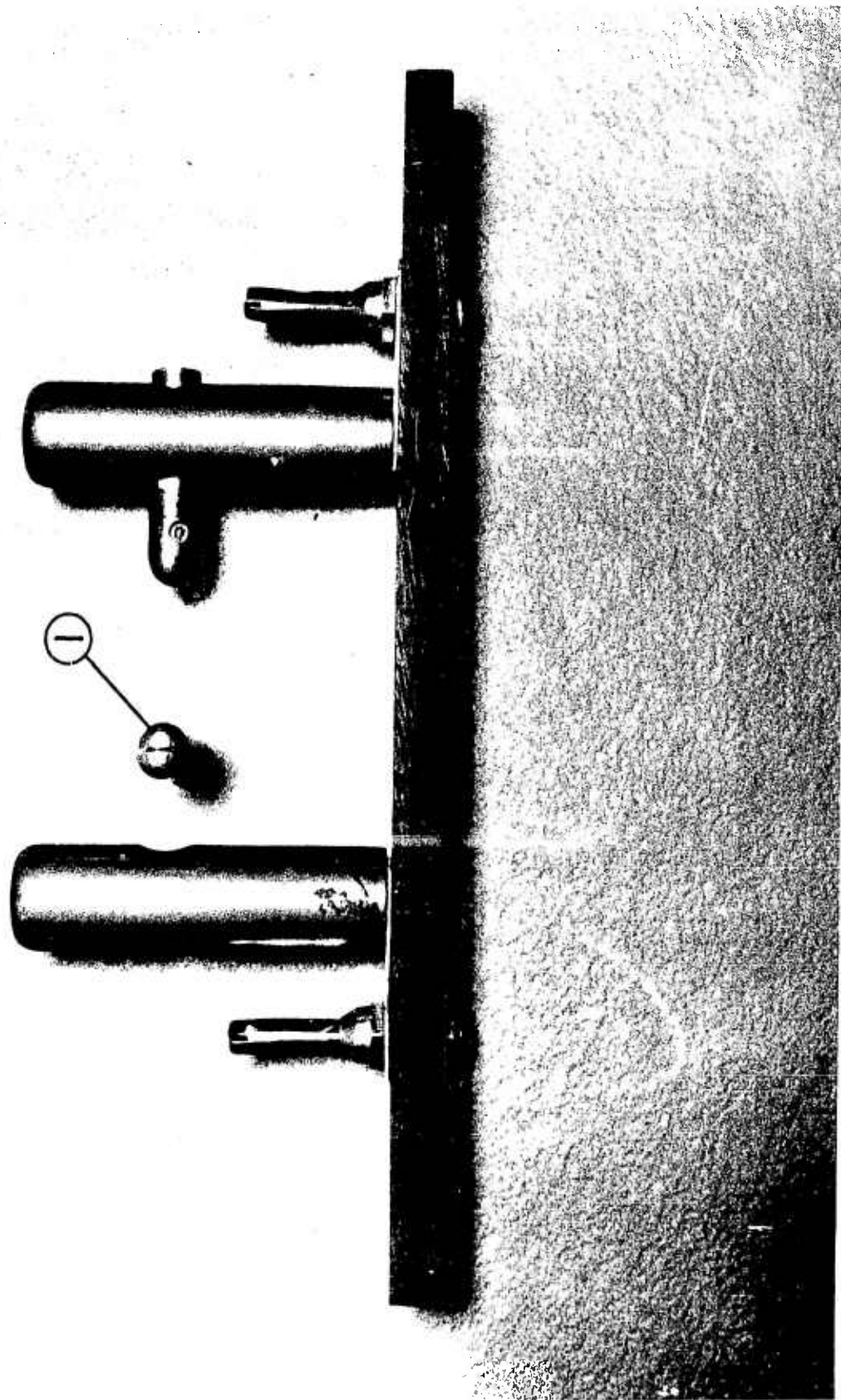
Fig. 2a. Wire Holder - l. wire clamp removed to show position of tungsten insert.
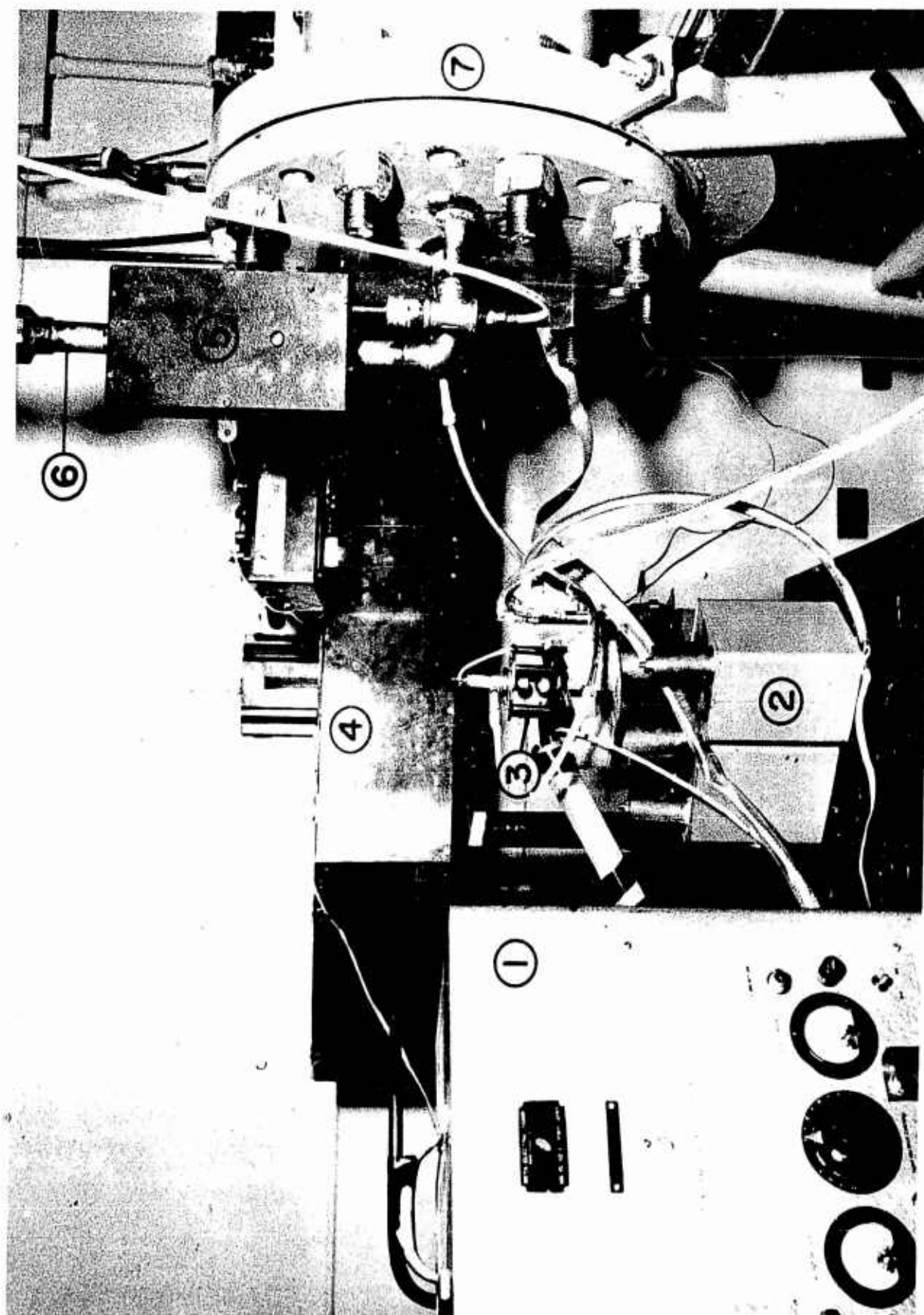
Fig. 3. 1. High voltage supply, 2. condensers, 3. triggering gap, 4. monochromator, 5. Pirani gauge, 6. vacuum line, 7. chamber.
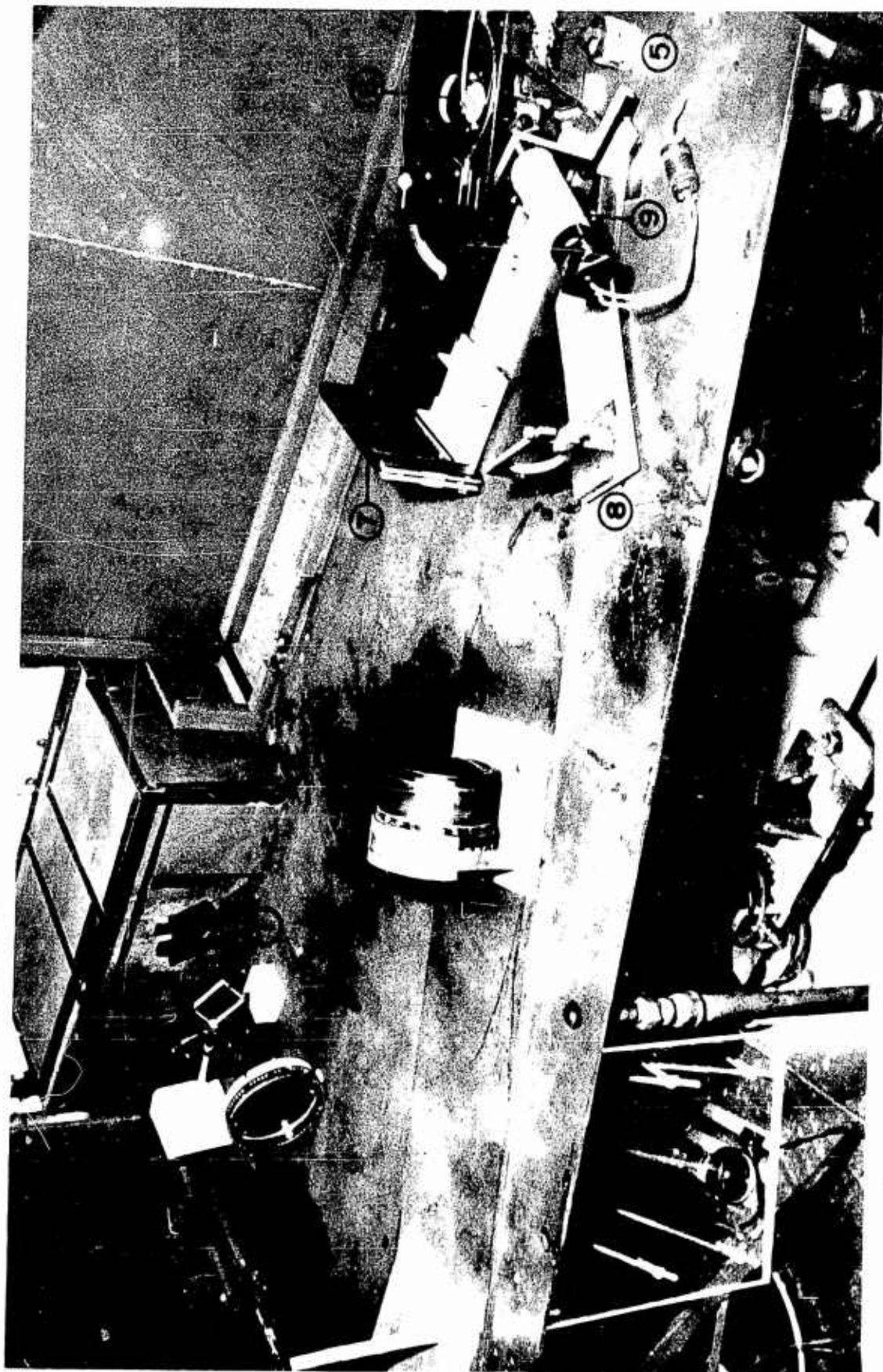
Fig. 4.   Streak Camera - 1. interference filter, 2. "minus blue" filter, 3. plane mirror, 4. lens, 5. rotating mirror removed from holder indicated below 6., 7. film holder, 8. levelling reference for adjusting fringes, 9. triggering light source.
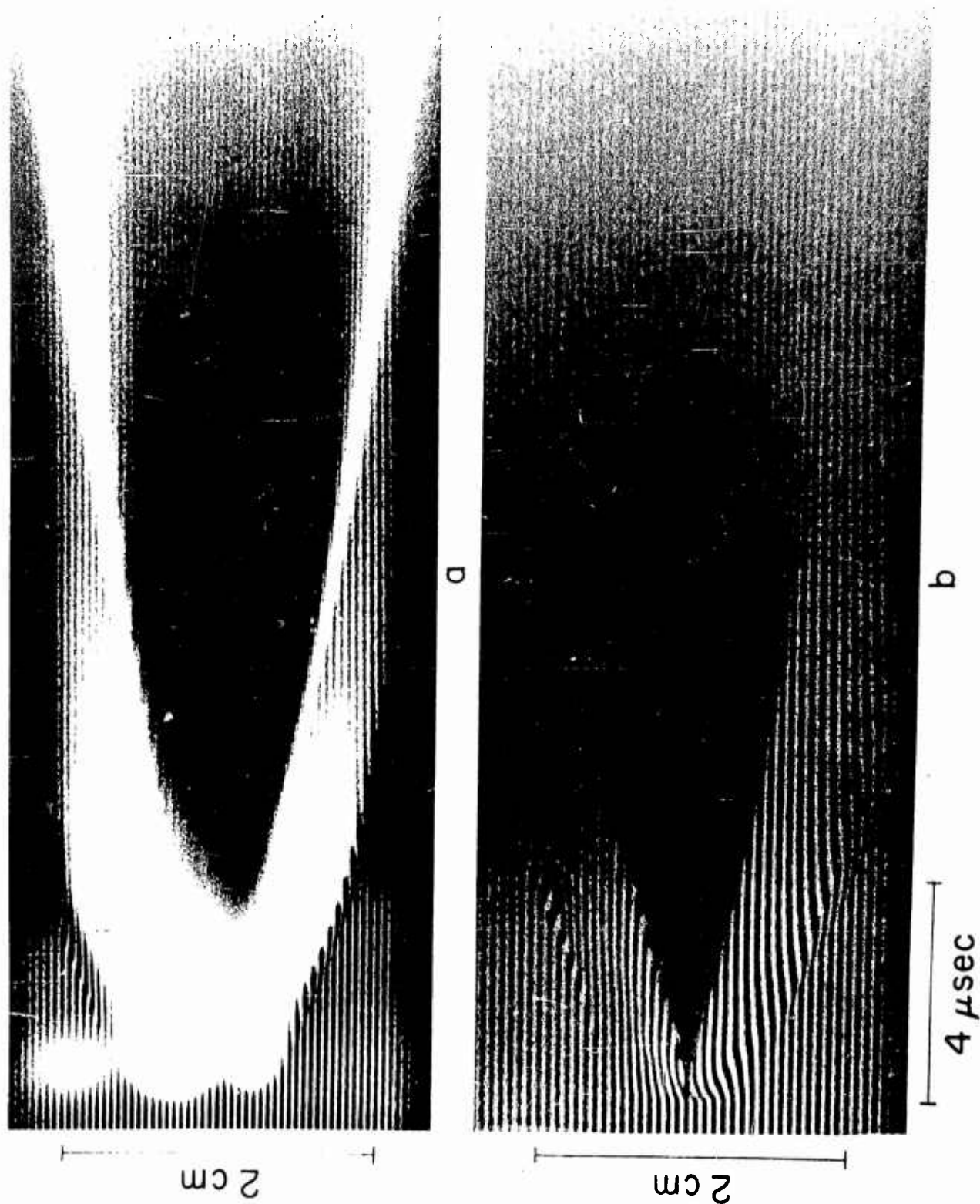
Fig. 5. Interferograms of 4 mil Cu Wire - a. 1/16 atm argon, 20 kv, no filter, b. same, with filters.
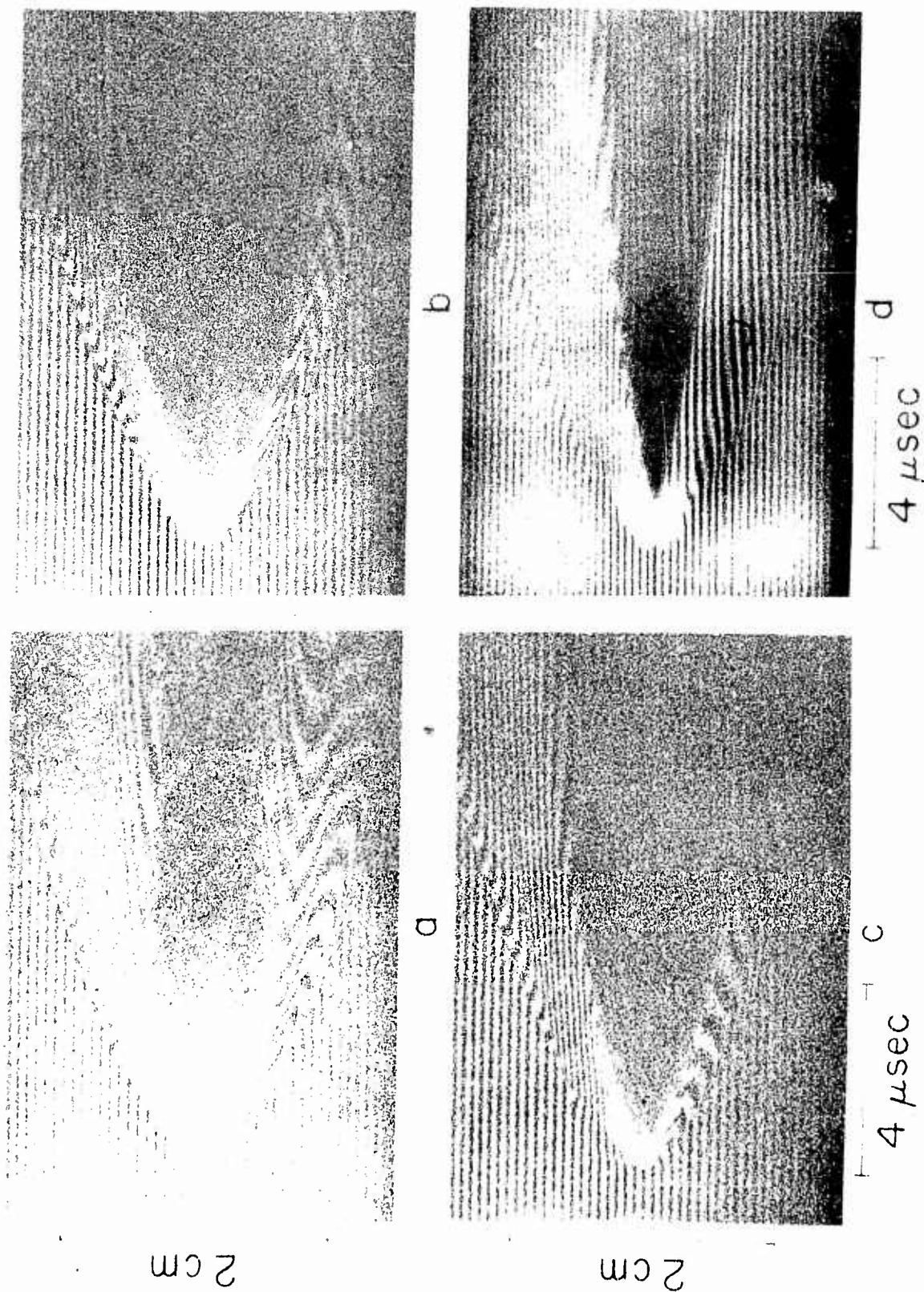
Fig. 6. Interferograms of 4 mil Cu Wire in Argon - a. 1 atm, b. 1/2 atm, c. 1/4 atm, d. 1/8 atm.

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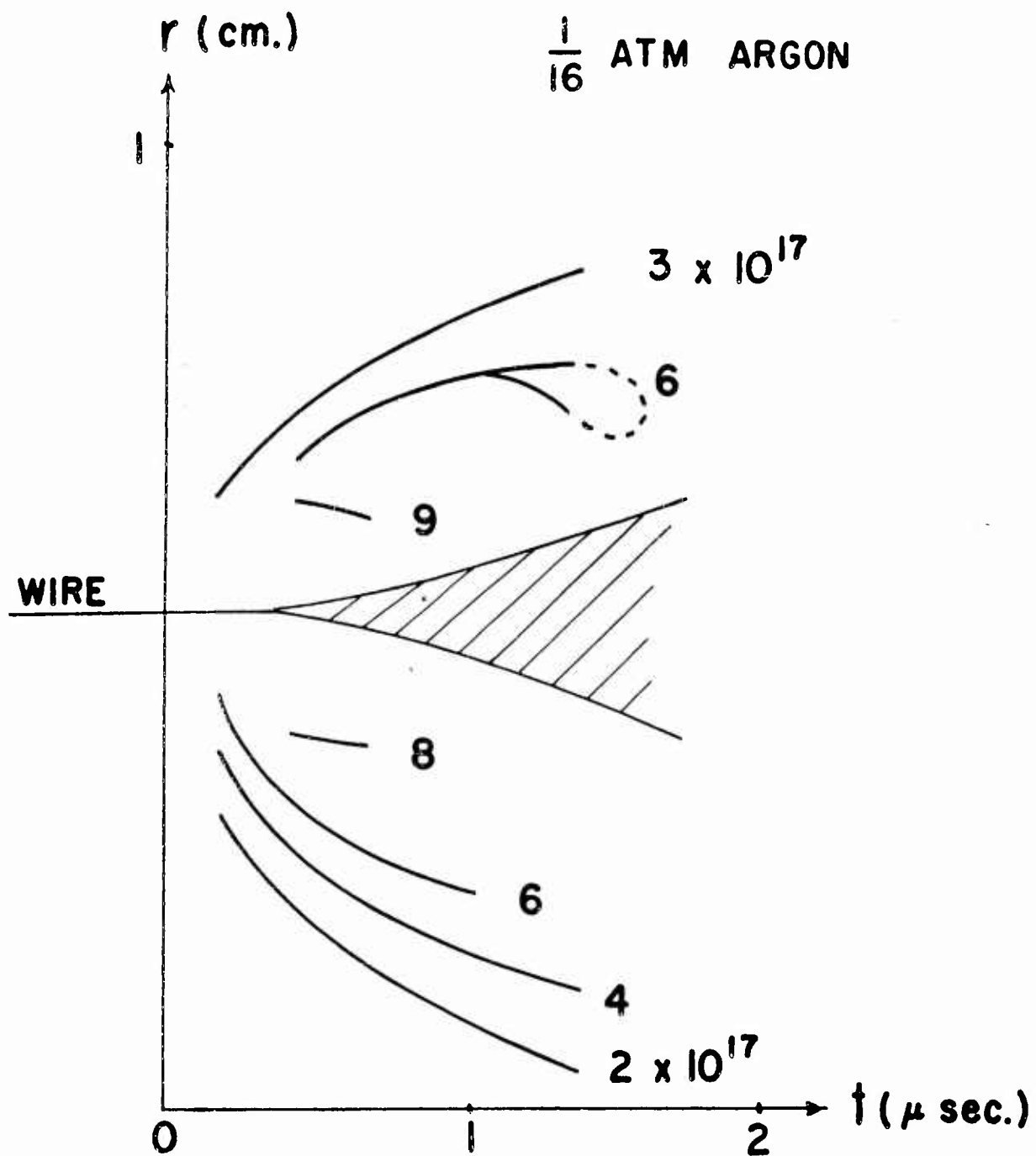
Fig. 7. Reduced Interferogram.

ELECTRON DENSITY CONTOURS
(PARTICLES / CC)
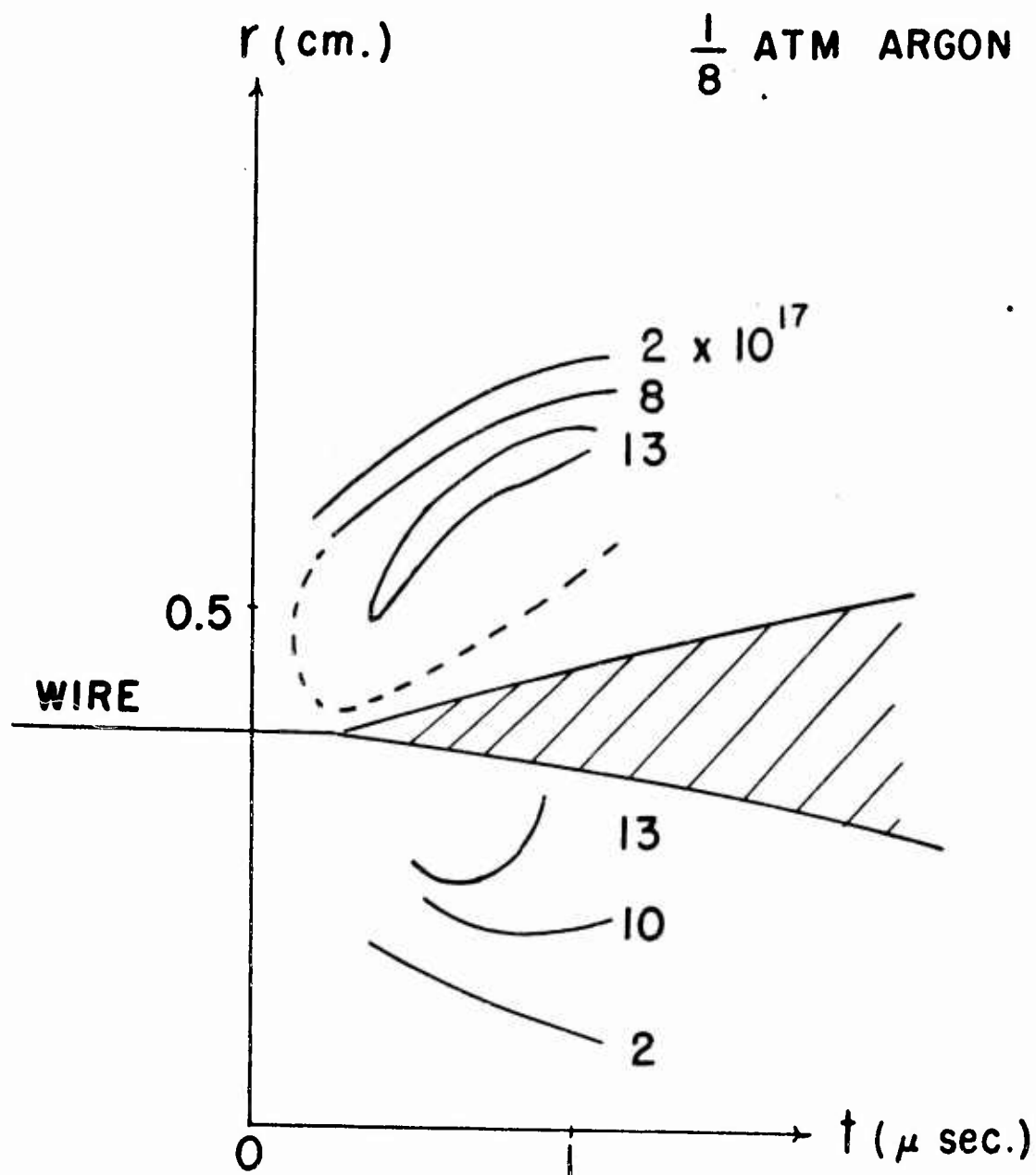
Fig. 8.   Reduced Interferogram.

ELECTRON DENSITY CONTOURS
(PARTICLES / CC)
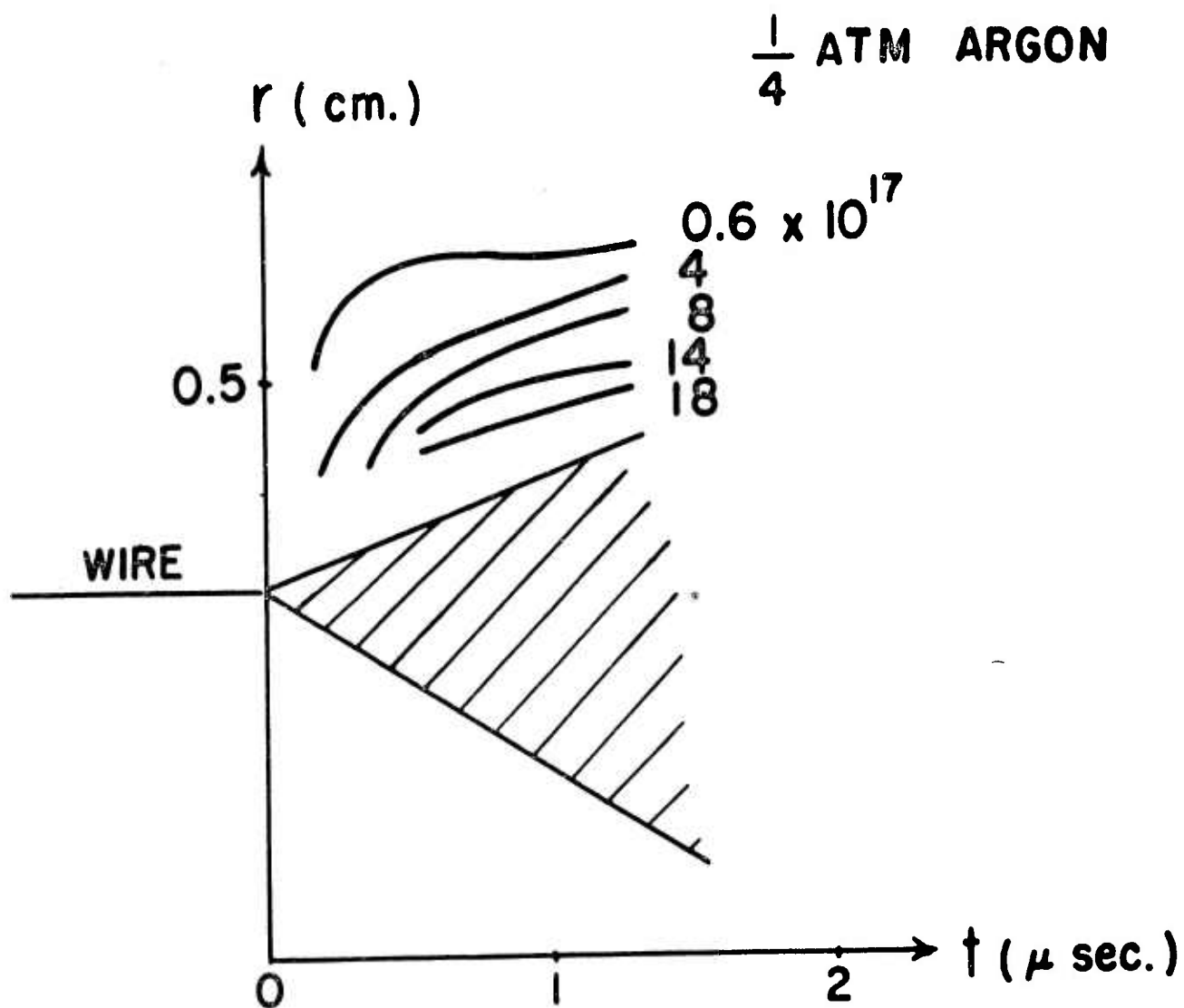
Fig. 9.   Reduced Interferogram.

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Shock waves from exploding wires at subatmospheric density ρ_0 show consider-
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are used to diminish the diffuse light from the glow, clear fringes can be reduced
in the entire glowing region. Near the tip, measured fringe-shifts are negative
indicating the presence of electrons. No shock wave is seen. During an interval
of about 1 usec fringe-shifts near the periphery of the expanding glow change to
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Exploding Wires
Shock Waves

Shock waves from exploding wires at subatmospheric density ρ_o show considerable deviations from the $\rho_o^{-1/4}$ dependence of shock radius expected on the basis of blast wave theory. The shock trajectory data are consistent with the assumption of time dependent energy addition and this fact suggests complexity in the mechanism of shock production. The recently discovered technique of streak interferometry has been applied to study 4 mil Cu wires exploded into argon at reduced pressures. Typical interferograms at 1/16 atm show an intensely luminous, peripheral arc formed in an annulus several millimeters from the wire. When filters are used to diminish the diffuse light from the glow, clear fringes can be reduced in the entire glowing region. Near the tip, measured fringe-shifts are negative indicating the presence of electrons. No shock wave is seen. During an interval of about 1 μsec fringe-shifts near the periphery of the expanding glow change to positive values and a compressional shock wave can be seen to separate and propagate ahead. Estimates obtained from approximate interferogram reductions indicate electron densities as high as 10^{18}/cc is the annular region of the arc.